JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

The Emergence of Cryptogams as Model Plants: A Scientific Perspective

Dr Saroj Rani
Botany Department, Navyug Kanya Mahavidyalaya Lucknow, India

Abstract: In recent years, cryptogams—including bryophytes, lichens, algae, fungi, and pteridophytes—have emerged as valuable model organisms in plant science research. Their simple structures, evolutionary significance, and genetic accessibility offer unique opportunities to advance our understanding of plant development, environmental adaptation, and phylogenetics. Historically overshadowed by angiosperms, cryptogams play crucial roles in ecosystem processes such as nutrient cycling, soil formation, and climate regulation. Their ability to thrive in diverse and extreme environments, coupled with their sensitivity to environmental changes, makes them effective bioindicators for assessing ecosystem health and the impacts of climate change. Recent advancements in molecular biology and genomic tools have further highlighted the potential of cryptogams to uncover genetic and metabolic pathways involved in stress tolerance, symbiosis, and adaptation mechanisms. Conservation initiatives, including the establishment of cryptogamic gardens and ex situ cultivation techniques, reflect a growing recognition of the importance of preserving these ancient plant lineages. Additionally, cryptogams hold significant promise in biotechnological applications, ranging from the development of biofertilizers and pharmaceuticals to enhancing climate-resilient crops. This review synthesizes current knowledge on the genetic, physiological, and ecological contributions of cryptogams to plant sciences, drawing on experimental findings related to genetic modifications and stress responses. By exploring their multifaceted roles, this paper emphasizes the potential of cryptogams to contribute substantially to both fundamental and applied research, advocating for their broader integration into mainstream botanical studies and conservation strategies.

Keywords: Cryptogams, Model Plants, Bryophytes, Pteridophytes, Biofertilizers, Genetic Studies, Evolutionary Biology.

1. Introduction:

The term "Cryptogams" is derived from the Greek words kryptos (hidden) and gamos (marriage), referring to their concealed reproductive structures. The non-flowering and non-seed-bearing plant group is known as cryptogams, or simply, flowerless and seedless plants. They include Thallophyta (algae, fungi, lichens), Bryophytes, and Pteridophytes.

Cryptogams, a diverse group of non-flowering and spore-producing plants, include bryophytes (mosses, liverworts, and hornworts), pteridophytes (ferns and their allies), lichens, algae, and fungi [1]. Unlike angiosperms, cryptogams lack seeds and often possess simpler anatomical structures, making them ideal model organisms for studying fundamental biological processes. Historically, plant science research has been dominated by angiosperms due to their agricultural importance and well-characterized genetics. However, the scientific community has increasingly recognized the significance of cryptogams for their evolutionary insights, ecological roles, and potential applications in biotechnology [2]. The renewed focus on cryptogams stems from their unique evolutionary positions, which bridge the gap between green algae and seed plants, offering valuable perspectives on plant evolution, adaptation, and genome complexity [3].

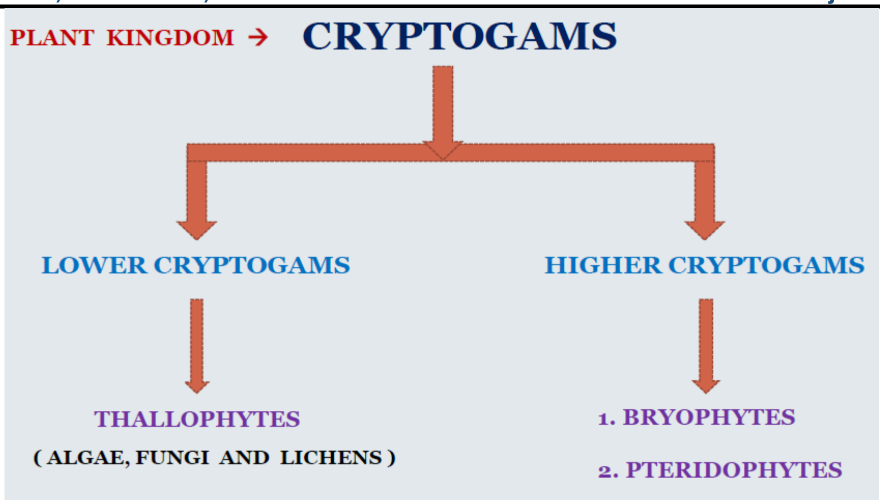

Figure 1: Types of Cryptogams

1.1 Evolutionary Significance of Cryptogams

Cryptogams represent some of the earliest land plants, having emerged over 400 million years ago. Their evolutionary history provides a window into the transition of plants from aquatic to terrestrial environments. The study of bryophytes, for example, has been instrumental in understanding the origin and diversification of land plants. Unlike vascular plants, bryophytes lack true roots and rely on simple rhizoids for anchorage and nutrient uptake, highlighting early adaptations to terrestrial life. Pteridophytes, with their vascular tissues but lack of seeds, serve as key models for exploring the evolution of vascular systems and reproductive strategies in plants. Additionally, lichens and fungi represent unique evolutionary lineages that showcase the complexity of symbiotic relationships and nutrient acquisition strategies [4]. The relatively simple genomes of many cryptogams, combined with advanced genomic and transcriptomic techniques, have made it feasible to dissect the genetic underpinnings of these evolutionary adaptations. By studying the genomes of cryptogams, researchers can identify conserved genes and regulatory networks that played crucial roles in plant evolution, providing a deeper understanding of the genetic innovations that enabled plants to colonize land [5].

1.2 Ecological Contributions and Bioindication

Cryptogams play vital roles in ecosystem functioning, particularly in nutrient cycling, soil formation, and climate regulation. In boreal and temperate forests, bryophytes and lichens significantly contribute to carbon and nitrogen cycling by fixing atmospheric nitrogen and storing organic matter. Their ability to colonize nutrient-poor and extreme environments—such as arctic tundras, deserts, and exposed rock surfaces—underscores their ecological versatility. Cryptogams also exhibit a remarkable ability to survive desiccation and rapidly resume metabolic activities upon rehydration, making them key components of biological soil crusts that prevent erosion and promote soil fertility [6].

Furthermore, the sensitivity of cryptogams to environmental changes makes them excellent bioindicators for monitoring ecosystem health. Lichens, for instance, are particularly sensitive to air pollutants like sulfur dioxide and heavy metals, serving as reliable indicators of air quality. Bryophytes, on the other hand, are effective indicators of soil and water acidity. Monitoring programs that utilize cryptogams provide valuable data for assessing the impacts of climate change, habitat fragmentation, and pollution. Their ability to reflect both acute and chronic environmental stressors allows for the early detection of ecological imbalances, enabling timely conservation actions [7].

1.3 Advances in Genetic and Molecular Research

Recent advancements in molecular biology have significantly expanded the potential of cryptogams as model organisms. The availability of whole-genome sequences for species such as *Physcomitrella patens* (a model moss) and *Marchantia polymorpha* (a model liverwort) has paved the way for comparative genomics and functional studies [8]. These models have been instrumental in exploring gene function, signalling pathways, and regulatory networks that are conserved across land plants. Gene editing technologies, including CRISPR/Cas9, have been successfully applied to cryptogams, facilitating targeted studies on gene function and stress responses [9].

Transcriptomic and proteomic analyses have further enriched our understanding of stress tolerance mechanisms in cryptogams, particularly their responses to drought, salinity, and temperature extremes. For instance, studies on desiccation-tolerant mosses have revealed a suite of protective proteins, antioxidants, and regulatory genes that mitigate cellular damage during dehydration [10]. These insights have potential applications in developing stress-resistant crops, thereby addressing agricultural challenges posed by climate change. Moreover, the simplicity of cryptogam genomes and the absence of genetic redundancy, often observed in angiosperms, allow for more straightforward interpretations of gene function and regulatory mechanisms [11].

1.4 Biotechnological Applications
The unique physiological and biochemical properties of cryptogams offer promising avenues for biotechnological applications. Algae and cyanobacteria, for example, are being explored for biofuel production due to their high lipid content and rapid growth rates. Bryophytes and lichens produce a variety of bioactive compounds, including antioxidants, antimicrobials, and anti-inflammatory agents, with potential applications in pharmaceuticals and cosmetics. Additionally, the ability of some cryptogams to bioaccumulate heavy metals suggests their utility in bioremediation of contaminated soils and water bodies [12].
In agriculture, the study of mycorrhizal fungi and their symbiotic associations with plant roots has provided insights into enhancing nutrient uptake and soil health. The potential to engineer crops with improved associations with such symbionts could revolutionize sustainable agriculture practices. Cryptogams' stress tolerance mechanisms also present opportunities to develop genetically modified crops that can withstand abiotic stresses like drought and salinity, which are increasingly relevant in the context of global climate change [13].

1.5 Conservation and Future Prospects
Conservation efforts focusing on cryptogams have gained momentum, recognizing their ecological importance and vulnerability to environmental disturbances. Initiatives such as cryptogamic gardens and ex situ conservation techniques aim to preserve endangered species and serve as living libraries for research. Educating the public and policymakers about the ecological roles of cryptogams is crucial for integrating them into broader conservation strategies [14].
Looking ahead, the integration of omics technologies, coupled with advanced imaging and bioinformatics tools, promises to unravel further the genetic and metabolic complexities of cryptogams. Developing comprehensive databases and collaborative research networks focused on cryptogams can accelerate discoveries and applications [15]. As the scientific community continues to explore the potential of these ancient lineages, cryptogams are poised to significantly influence our understanding of plant biology and offer practical solutions to environmental challenges. Thus, the emergence of cryptogams as model plants not only enriches plant sciences but also holds promise for addressing key challenges in sustainability and conservation [16].

2. Literature Survey:
The use of cryptogams in scientific research has expanded significantly over the last few decades. Mosses such as *Physcomitrella patens* have become model systems for genetic studies due to their efficient homologous recombination and well-characterized genome. Liverworts and hornworts provide insights into the early evolution of land plants, while ferns like *Ceratopteris richardii* serve as models for studying sporophyte development.
Research has demonstrated the potential of cryptogams in biotechnology, including biofuel production, environmental monitoring, and pharmaceutical applications. For example, certain algae species have been investigated for their potential in carbon sequestration and biofuel production. Similarly, fungi have been widely used in genetic research, providing insights into metabolic pathways and industrial enzyme production.
This section reviews key studies that establish cryptogams as model organisms in plant sciences, with an emphasis on their molecular biology, environmental adaptation, and industrial relevance.

Cerrejón et al., presented in [17], reviews the role of citizen science (CS) in botanical research from 2012 to 2022, highlighting a significant growth in CS contributions, with an annual increase of about 40%. However, it reveals a strong bias towards vascular plants, with only 58 out of 304 studies focusing on non-vascular cryptogams like bryophytes, lichens, fungi, and algae. Challenges such as species identification and low public awareness limit non-expert contributions. The paper calls for more methodological studies and public engagement to leverage CS for cryptogam research, emphasizing their ecological importance.

Tomkins et al., presented in [18], the complexity of plant systems, emphasizing the need to understand emergent properties that arise from interactions among components like branches, roots, and cellular processes. It argues that current computational tools and modeling approaches are inadequate for managing multiscale interactions or predicting new emergent properties. The authors advocate for developing advanced methodologies to bridge these gaps and enhance our understanding of plant growth and development.

Qu et al., describe in [19], the vital roles of cryptogams—lichens, liverworts, and mosses—in maintaining ecosystem stability, especially in harsh environments. Cryptogams influence soil properties by regulating moisture and enhancing fertility through increased levels of organic carbon, nitrogen, phosphorus, and other nutrients. They also impact vascular plant regeneration by acting as physical barriers, providing shade, competing for resources, releasing growth-inhibiting chemicals, and supporting ectomycorrhizal fungi development. The review highlights the need for further research into these complex interactions.

Thakur et al., presented in [20], explores the diversity and significance of cryptogams—algae, bryophytes, lichens, and pteridophytes—in this area. Highlighting a research gap, the study systematically collected and identified 200 specimens across 18 localities, revealing 45 species: 9 algae, 10 bryophytes, 7 lichens, and 19 pteridophytes. The findings underscore the ecological and medicinal importance of these plants, advocating for further research and conservation efforts to preserve their biodiversity and potential benefits.

Zamani et al., presented in [21], examines the potential of cryptogams in nanofabrication, emphasizing their active metabolites with bio-reductive properties. It highlights the dual role of cryptogams in ethnomedicine and nanotechnology, exploring techniques for creating nanostructures and their pharmacological applications. The paper calls for further research to harness these untapped biological resources for innovative nanofabrication processes.

Deane-Coe et al., presented in [22], highlights the crucial roles of cryptogams—bryophytes, lichens, and soil crusts—in ecosystem processes such as carbon and nitrogen cycling. It emphasizes the importance of functional trait analyses to understand how cryptogams influence soil stability, fertility, and biogeochemical cycles. The study distinguishes between response traits (supporting growth and reproduction) and effect traits (influencing ecosystems), showing that cryptogam traits can predict community structure and diversity. Sensitive to environmental changes, especially in nitrogen fixation, cryptogams require more focused research. The authors advocate for a comprehensive trait database to better understand cryptogams' ecological functions.

Simmel et al., presented in [23], highlights the importance of cryptogams—bryophytes, lichens, and macromycetes—in assessing ecosystem health and guiding conservation efforts. It introduces a new method for calculating Ellenberg Indicator Values (EIVs) for macromycetes and explores their functional traits to understand ecological roles and vulnerability. The study finds that cryptogam communities are more stable than vascular plants under different land-use histories. It also identifies effective management practices, such as controlled burning and selective mowing, to enhance cryptogam diversity. Overall, the paper emphasizes the potential of cryptogams as reliable bioindicators and calls for targeted conservation strategies.

Schlensog et al., investigates in [24], how water sources influence the activity and environment of cryptogams on Léonie Island in the maritime Antarctic. It highlights that Antarctic vegetation is primarily composed of cryptogams, which depend on water availability for metabolic activity. By monitoring various species over 21 days, the study found that hydration type—meltwater or precipitation—significantly affected active periods. Microclimatic factors like light and temperature also influenced activity patterns. The findings suggest that water availability is more critical than temperature for controlling the distribution and productivity of Antarctic vegetation, offering insights into how these ecosystems might respond to climate change.

Lang et al., presented in [25], emphasizes the significant impact of climate change on cryptogams—bryophytes and lichens—in the (Sub) Arctic, where warming is rapid and extreme. Cryptogams, dominant in these regions, are vital for regulating hydrology, carbon balance, nitrogen fixation, and permafrost preservation. Despite their importance, cryptogams have been largely neglected in climate research compared to vascular plants. The paper highlights how changes in cryptogam diversity and abundance could profoundly affect nutrient cycling and carbon dynamics, underscoring the need for more focused studies on their ecological roles.

McMullan-Fisher et al., describe in [26], the need to include cryptogams—mosses and macrofungi-in conservation strategies. Conducted in Tasmania's Hobart region, the study analyzed the relationships between these groups and environmental factors across different vegetation types. It found that canopy cover, along with altitude and geology, were strong predictors of cryptogam presence. While selecting 30% of sites could effectively conserve common species, uncommon taxa showed weak associations with vascular plants, indicating a need for targeted conservation efforts. Further research on rare taxa is recommended.

Cove et al., presented in [27], highlights *Physcomitrella patens* as a valuable model organism for studying plant development and genomics due to its haploid life cycle, which simplifies genetic analysis. Widely used in research for over 80 years, *P. patens* has benefited from advancements in gene targeting and RNA interference. Despite its simple structure and lack of vascular tissues and seeds, it shares many signalling pathways with flowering plants, making it useful for comparative studies. The paper emphasizes the potential of *P. patens* in understanding plant evolution and applying insights to crop breeding and agriculture.

Suetsugu et al., describe in [28], how phototropin and phytochrome photoreceptors regulate photomovement responses in cryptogamic plants—ferns, mosses, and green algae—to optimize light capture for photosynthesis. Phototropins, which respond to blue light, control phototropism, chloroplast movement, and stomatal opening, while phytochromes respond to red light, influencing similar processes. The discovery of NEOCHROME, a chimeric photoreceptor in some ferns and algae, highlights the ability of these plants to utilize both red and blue light. The paper underscores the complexity and evolutionary significance of these light-sensing mechanisms in enhancing photosynthesis under low-light conditions.

Recent research has highlighted the potential of cryptogams—non-vascular plants such as bryophytes, lichens, and algae—as model organisms in plant science. The following table summarizes key studies.

Year	Title	Outcomes	Research Gap
2024	Chromosomal evolution in Cryptangieae Benth. (Cyperaceae): Evidence of holocentrism and pseudomonads [29]	Identified holocentric chromosomes and pseudomonads in Cryptangieae, suggesting unique chromosomal evolution. The study explores chromosomal structures using cytogenetic analysis, including chromosome counting and fluorescence in situ hybridization (FISH).	Limited understanding of the functional implications of holocentric chromosomes in plant development and evolution.
2024	Cryptogams as bio-indicators for ecosystem monitoring in Sri Lanka: a comprehensive review and recommendations [30]	Highlighted the potential of cryptogams as sensitive bio-indicators for monitoring ecosystem health in Sri Lanka, emphasizing their responses to environmental stressors. Used a comprehensive literature review and analysis of cryptogam responses to pollution, climate change, and land-use changes.	Lack of baseline data on cryptogam diversity and abundance in Sri Lanka; need for integrating modern molecular techniques in monitoring programs.
2023	Development of a growth chamber for cryptogams: a step toward ex situ conservation [31]	Designed a low-cost, solar-powered growth chamber for ex situ conservation of cryptogams, maintaining optimal growth conditions. The methodology involved constructing a controlled growth chamber with regulated temperature, humidity, light, and rainwater harvesting	Need for long-term studies to assess the effectiveness of ex situ conservation methods on cryptogam survival and adaptation.
2022	Warming enhances dominance of vascular plants over cryptogams across northern wetlands [32]	Found that climate warming increases biomass of vascular plants while reducing that of cryptogams, potentially altering ecosystem functions. Conducted a meta-analysis of observations from 273 sites, examining plant biomass responses to warming.	Limited understanding of the long-term implications of reduced cryptogam presence on wetland ecosystem services.
2020	What do tropical cryptogams reveal? Strong genetic structure in Amazonian bryophytes [33]	Discovered significant spatial genetic structure in Amazonian bryophytes, challenging the assumption of high dispersal capabilities. Used SNP data analysis from 10 species with RADseq.	Need to reassess conservation strategies considering the limited dispersal and genetic isolation of tropical bryophytes.

2017	Functional ecology of cryptogams: scaling from bryophyte, lichen, and soil crust traits to ecosystem processes [34]	Emphasized the importance of cryptogam traits in ecosystem processes. Reviewed and synthesized existing literature on their functional traits and ecological roles.	Lack of standardized protocols for measuring cryptogam traits to facilitate comparative studies.
2016	Marchantia polymorpha L.: An Emerging Model Plant System to Study Contemporary Plant Biology – A Review [35]	Highlighted the potential of *Marchantia polymorpha* as a model system due to its simple structure and ease of genetic manipulation. The study was a comprehensive literature review on its biological characteristics and applications.	Need for development of more genetic tools and resources to fully utilize *Marchantia polymorpha* as a model system.
2015	Comparative cryptogam ecology: a review of bryophyte and lichen traits that drive biogeochemistry [36]	Reviewed the functional traits of bryophytes and lichens influencing biogeochemical cycles, highlighting their roles in nutrient cycling and ecosystem processes. Based on a comprehensive literature review and synthesis.	Limited empirical data on specific trait-environment relationships in diverse ecosystems.

These studies underscore the ecological significance of cryptogams and their potential as model organisms in plant research. However, further research is essential to address existing gaps and fully harness their potential in ecological monitoring and conservation efforts.

3. Results and Discussion:

Recent advancements in cryptogam research have significantly deepened our understanding of their genetics, physiology, and ecological roles, highlighting their importance as model organisms in plant science. Genomic studies on cryptogams like Physcomitrella patens and Marchantia polymorpha have unveiled key regulatory pathways that were essential for the transition of plants from aquatic to terrestrial environments. These pathways include mechanisms for desiccation tolerance, UV protection, and stress responses, suggesting that these adaptations played a crucial role during early land colonization. The simple morphology and evolutionary positions of cryptogams make them valuable systems for exploring the origins of traits such as stomata and vascular tissues. However, differences in genome architecture and regulatory mechanisms between cryptogams and vascular plants pose challenges for direct translational applications, necessitating more comparative studies. The genetic tractability of cryptogams, especially the efficient homologous recombination observed in P. patens, has been a significant advantage for functional genomics research. The integration of CRISPR/Cas9 technology has further enabled precise gene editing, allowing researchers to investigate stress responses, metabolic pathways, and developmental processes with greater accuracy. These advancements not only support the use of cryptogams as model organisms for basic plant biology but also open avenues for translational research aimed at enhancing crop resilience. Ecologically, cryptogams play vital roles in nutrient cycling, soil stabilization, and carbon sequestration. Moss-dominated biocrusts, for instance, significantly contribute to nitrogen fixation and organic carbon inputs, especially in arid and semi-arid regions. Lichens, with their unique symbiotic relationships, efficiently colonize bare substrates and recycle nutrients, demonstrating remarkable resilience in extreme environments. Their sensitivity to pollutants such as heavy metals and nitrogen compounds also makes cryptogams effective bioindicators for monitoring air quality and assessing ecosystem health. In the field of biotechnology, cryptogams present promising prospects due to their production of bioactive compounds with antimicrobial, antioxidant, and pharmaceutical potential. The mechanisms underlying their desiccation tolerance could inform strategies to develop stress-resistant crops. However, challenges such as large-scale cultivation and efficient extraction of these compounds need to be addressed. Conservation efforts focusing on cryptogams are equally important, given their ecological significance and contributions to biodiversity. Expanding ex situ conservation strategies and integrating cryptogams into broader conservation frameworks could help preserve their genetic diversity and ecological functions. Collectively, these findings underscore the need for continued research into cryptogams to harness their full potential for ecological management, biotechnology, and agricultural sustainability.

4. Conclusion:

Cryptogams, including bryophytes, lichens, algae, and fungi, have emerged as indispensable model organisms in modern plant research due to their evolutionary significance, genetic accessibility, and ecological roles. Their simple morphology and phylogenetic positions provide valuable insights into the transition from aquatic to terrestrial life and the origins of key plant traits. Recent advancements in genetic tools, such as CRISPR/Cas9, have significantly enhanced their utility in functional genomics, enabling precise studies of stress responses, metabolic pathways, and developmental processes. Ecologically, cryptogams play crucial roles in nutrient cycling, soil stabilization, and carbon sequestration, while their sensitivity to pollutants makes them effective bioindicators for monitoring environmental health. Moreover, their production of bioactive compounds and mechanisms of desiccation tolerance present promising biotechnological applications, including the development of stress-resistant crops and novel pharmaceuticals. However, challenges like limited genomic resources and scalable cultivation methods must be overcome to fully harness their potential. Future research should focus on expanding genomic resources, exploring biotechnological applications, and integrating cryptogam studies into broader plant science research. Additionally, adopting interdisciplinary approaches that combine cryptogam research with bioinformatics, environmental science, and biotechnology could offer innovative solutions for sustainable resource management and climate resilience. Prioritizing conservation strategies to preserve cryptogam biodiversity is also essential, given their significant ecological contributions. Integrating cryptogams into mainstream botanical research and conservation efforts could lead to ground-breaking discoveries in plant adaptation, stress tolerance, and sustainable agriculture, addressing contemporary environmental challenges effectively.

References

[1] Rensing, S. A. (2018). Great moments in evolution: the conquest of land by plants. *Current Opinion in Plant Biology*, *42*, 49–54.

[2] Bowman, J. L., Kohchi, T., Yamato, K. T., et al. (2017). Insights into land plant evolution garnered from the Marchantia polymorpha genome. *Cell*, *171*(2), 287–304.

[3] Delwiche, C. F., & Cooper, E. D. (2015). The Evolutionary Origin of a Terrestrial Flora. *Current Biology*, *25*(19), R899–R910.

[4] Spribille, T., Tuovinen, V., Resl, P., et al. (2016). Basidiomycete yeasts in the cortex of ascomycete macrolichens. *Science*, *353*(6298), 488–492.

[5] Stark, L. R. (2017). Phenotypic and genotypic variation in desiccation tolerance of bryophytes. *Frontiers in Plant Science*, *8*, 2112.

[6] Sakakibara, K., Ando, S., Yip, H. K., et al. (2014). The liverwort Marchantia polymorpha: Past, present, and future. *Plant and Cell Physiology*, *55*(1), 7–20.

[7] Prigge, M. J., & Bezanilla, M. (2010). Evolutionary crossroads in developmental biology: Physcomitrella patens. *Development*, *137*(21), 3535–3543.

[8] Cirri, E., & Pohnert, G. (2019). Algae-bacteria interactions that balance the planktonic microbiome. *New Phytologist*, *223*(1), 100–106.

[9] Dragone, G., Fernandes, B., Vicente, A. A., & Teixeira, J. A. (2010). Third generation biofuels from microalgae. *Current Research, Technology and Education Topics in Applied Microbiology and Microbial Biotechnology*, *2*, 1355–1366.

[10] Van der Heijden, M. G., & Horton, T. R. (2009). Socialism in soil? The importance of mycorrhizal fungal networks for facilitation in natural ecosystems. *Journal of Ecology*, *97*(6), 1139–1150.

[11] Xu, J., & Xue, C. (2019). Improving drought tolerance in crops using genetic engineering approaches. *Plant Biotechnology Journal*, *17*(5), 832–849.

[12] Glime, J. M. (2017). *Bryophyte Ecology*. Michigan Technological University and the International Association of Bryologists.

[13] Benitez, A., & Snyder, J. (2016). Public perceptions of bryophytes: Knowledge, uses, and conservation. *Biodiversity and Conservation*, *25*(5), 1027–1045.

[14] De Vries, J., de Vries, S., Curtis, B. A., & Archibald, J. M. (2018). Plant and algal genomics: Exploring the last frontier of photosynthetic eukaryotes. *Nature Reviews Genetics*, *19*(11), 671–683.

[15] Reski, R., Lang, D., & Rensing, S. A. (2018). The road to next-generation model systems: Bryophytes lead the way. *Current Opinion in Plant Biology*, *42*, 1–7.

[16] Patiño, J., Vanderpoorten, A., & Shaw, A. J. (2018). The future of bryophyte research: Challenges and opportunities. *New Phytologist*, *218*(2), 423–429.

[17] Cerrejón, C., Noualhaguet, M., Fenton, N. J., Indorf, M. F., & Feldman, M. J. (2025). Inconspicuous taxa in citizen science-based botanical research: actual contribution, limitations, and new opportunities for non-vascular cryptogams. *Frontiers in Environmental Science*, *12*, 1448512.

[18] Tomkins, M. (2023). Towards modelling emergence in plant systems. Quantitative Plant Biology, 4. https://doi.org/10.1017/qpb.2023.6

[19] Qu, M., Duan, W., & Chen, L. (2023). The Role of Cryptogams in Soil Property Regulation and Vascular Plant Regeneration: A Review. Applied Sciences. https://doi.org/10.3390/app14010002

[20] Thakur, P., & Chander, H. (2020). Floristic Studies on Cryptogams of Sujanpur-Tihra region of Himachal Pradesh. 8(2), 17–20. https://doi.org/10.33980/AJABS.2020.V08I02.004

[21] Zamani, S., Jha, B., Jha, A. K., & Prasad, K. (2018). Nanofabrication by Cryptogams: Exploring the Unexplored (pp. 81–108). Springer, Cham. https://doi.org/10.1007/978-3-319-99570-0_5

[22] Deane-Coe, K. K., & Stanton, D. E. (2017). Functional ecology of cryptogams: scaling from bryophyte, lichen, and soil crust traits to ecosystem processes. New Phytologist, 213(3), 993–995. https://doi.org/10.1111/NPH.14408

[23] Simmel, J. (2017). Cryptogams as indicator organisms in ecology and conservation biology. https://epub.uni-regensburg.de/35124/

[24] Schlensog, M., Green, T. G. A., Green, T. G. A., & Schroeter, B. (2013). Life form and water source interact to determine active time and environment in cryptogams: an example from the maritime Antarctic. Oecologia, 173(1), 59–72. https://doi.org/10.1007/S00442-013-2608-9

[25] Lang, S. I. (2011). Global change and the functional diversity of cryptogams in northern biomes. https://www.narcis.nl/research/RecordID/OND1297673

[26] McMullan-Fisher, S. (2008). Surrogates for cryptogam conservation - associations between mosses, macrofungi, vascular plants and environmental variables. https://eprints.utas.edu.au/8282/

[27] Cove, D. J., Perroud, P.-F., Charron, A. J., McDaniel, S. F., Khandelwal, A., & Quatrano, R. S. (2009). The Moss Physcomitrella patens: A Novel Model System for Plant Development and Genomic Studies. CSH Protocols, 2009(2). https://doi.org/10.1101/PDB.EMO115

[28] Suetsugu, N., & Wada, M. (2006). Phytochrome-dependent photomovement responses mediated by phototropin family proteins in cryptogam plants. Photochemistry and Photobiology, 83(1), 87–93. https://doi.org/10.1562/2006-02-27-IR-817

[29] Chaves, A. L. A., Ferreira, M. T. M., Escudero, M., Luceño, M., & Costa, S. M. (2024). Chromosomal evolution in Cryptangieae Benth.(Cyperaceae): Evidence of holocentrism and pseudomonads. Protoplasma, 261(3), 527-541.

[30] Dilrukshi, H. A. C., Ruklani, N. C. S., & Rubasinghe, S. C. K. (2024). Cryptogams as bio-indicators for ecosystem monitoring in Sri Lanka: a comprehensive review and recommendations. Environmental Monitoring and Assessment, 196(12), 1-14.

[31] Samanta, S., Panchadhyaee, P., Maity, T. R., Nanda, K., & Samanta, A. (2023). Development of a growth chamber for cryptogams: a step toward ex situ conservation. Brazilian Journal of Botany, 46(3), 661-666.

[32] Bao, T., Jia, G., & Xu, X. (2022). Warming enhances dominance of vascular plants over cryptogams across northern wetlands. Global Change Biology, 28(13), 4097-4109.

[33] Ledent, A., Gauthier, J., Pereira, M., Overson, R., Laenen, B., Mardulyn, P., ... & Vanderpoorten, A. (2020). What do tropical cryptogams reveal? Strong genetic structure in Amazonian bryophytes. New Phytologist, 228(2), 640-650.

[34] Deane-Coe, K. K., & Stanton, D. (2017). Functional ecology of cryptogams: scaling from bryophyte, lichen, and soil crust traits to ecosystem processes. New Phytologist, 213(3), 993-995.

[35] Alam, A., & Pandey, S. (2016). Marchantia polymorpha L.: an emerging model plant system to study contemporary plant biology–a review. Plant Science Today, 3(2).

[36] Cornelissen, J. H., Lang, S. I., Soudzilovskaia, N. A., & During, H. J. (2007). Comparative cryptogam ecology: a review of bryophyte and lichen traits that drive biogeochemistry. Annals of botany, 99(5), 987-1001.